

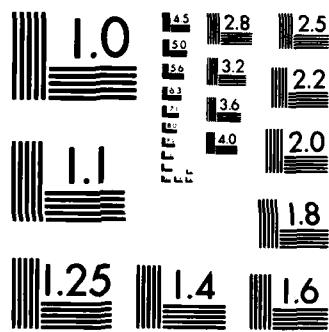
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| We present measurements of the output properties of two types of new low noise noncommercially available Hitachi diode lasers. Measurements of the intensity and phase noise of lasers running with or without optical feedback are described. | | |

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INTENSITY NOISE AND SPECTRAL PROPERTIES OF LOW NOISE GaAlAs LASERS

INTRODUCTION

The small size, high efficiency, and high output power of solid-state single mode diode lasers make them a convenient source for many fiber optic and related systems. At NRL, in the Fiber Optic Sensor System (FOSS) Program, diode lasers have been used as sources in fiber optic interferometer sensors.¹ However, both the free-running intensity² and frequency instabilities^{3,4} of these lasers impose restrictions on the design of these sensor systems.^{1,4,5} It has also been shown that small amounts of optical feedback into the laser cavity can induce excess noise,⁶ mode hopping,^{6,7} satellite mode generation⁷ as well as line narrowing,^{8,9,10} and broadening.⁷ Many of the optical feedback induced effects can be induced from the Rayleigh backscatter^{11,12} along the fiber from which the sensor is constructed. In this report, the output characteristics of six low noise Hitachi CSP lasers (not yet commercially available) with and without optical feedback are presented. The results are discussed in terms of the suitability of these devices for use in fiber-optic sensor systems.

LASERS

The lasers tested and reported here were designed by Hitachi for low noise operation. While the specific laser structure is proprietary, the basic channel substrate planar structure was modified to fix laser output on a single longitudinal mode over a wide operating current range. Although a current change produced a proportional variation in the output frequency of the laser, emission was held to a specific single longitudinal mode thus eliminating mode hopping, a major source of amplitude noise in the free-running laser. The ability to induce mode hopping by optical feedback was observed to be relatively unaffected by the alterations in the laser structure as will be discussed later. Three variations of this laser structure were tested and are reported here, *Q*, *Y* and *M* type CSP lasers. For these particular lasers, developed to operate in the visible range of the spectrum, the lasing wavelength is near 750 nm.

MEASUREMENTS

The free-running intensity noise was determined for each of the six lasers at 1 kHz as a function of laser drive current. The frequency dependence of the intensity noise at $1.2 I_{th}$ and $1.4 I_{th}$ was also determined for the six devices. The magnitude of the frequency instabilities was determined for one of the lowest noise lasers (Y197/2) as well as its variation with laser drive current. The spectral characteristics of two of the lasers (Y197/2 and 1MS31) were measured using a Fabry-Perot as a function of optical feedback into the laser cavity. Finally, using a reflector in close proximity to the diode facet to cause the laser to hop between longitudinal modes, the excess intensity noise was measured. The measurements are discussed in detail below.

MEASUREMENT OF INTENSITY NOISE

The intensity noise measurements were obtained by detecting the laser output with a large area (1 cm^2) Si photodiode. The photodiode was operated photoconductively with a $10^4 \Omega$ load resistance

biased at 9V and was placed within 1 cm of the laser facet. A large area detector was used to ensure that most of the radiation emitted from the laser facet was collected by the photodetector. For laser outputs in excess of 1 mW, a neutral density filter was placed between the laser and photodetector to keep the photodetector response in the linear region. The linearity of the detection system was verified by using two polarizers and applying Malus' Law. Care was taken to ensure that optical feedback into the laser cavity was minimized as this could produce a spurious noise effect.⁶ The output of the photodetector was analyzed using a Hewlett Packard 3582A spectrum analyzer. For measurements of the amplitude noise below the laser threshold, a low noise amplifier was used before the spectrum analyzer.

The spectrum analyzer gave an output in terms of a measured value of dBV (dBV_{mea}), which was dependent on the output voltage of the photodetector V . A convenient parameter to define the laser noise is the relative laser noise (i.e., dI/I where I is the dc component of the laser intensity and dI is the rms fluctuation of the intensity at a frequency f), as this corresponds to a noise-to-signal ratio. However, it is the convention in noise studies to use the electrical noise power generated (in this case generated by the laser radiation incident on the photodetector) by the detector (i.e., proportional to $(dI)^2$). Consequently, the following equation was used to calculate the relative noise output in dB.

$$\text{dB} = 20 \log \frac{dV}{V} = \text{dBV}_{\text{mea}} - 20 \log (V)$$

where dV is the rms voltage fluctuation (noise) of the photodetector which is proportional to dI . Thus a 10^{-5} intensity fluctuation corresponds to -100 dB. All the results presented were subsequently normalized to a 1 Hz bandwidth.

To characterize the noise properties of the photodetector, a stable white light source was used to illuminate the photodiode (a similar intensity to that obtained with the lasers was used). The resultant frequency spectrum obtained from the spectrum analyzer indicated that the detection scheme was shot noise limited (at these light levels), the shot noise being approximately 10 dB greater than the intrinsic noise of the spectrum analyzer. The experimentally determined value of the shot noise agreed to within ± 1 dB of that calculated from theory.

Figure 1a-f shows the characteristic output curves for the six lasers investigated; also shown is the value of the relative laser noise in dB at 1 kHz with a 1 Hz bandwidth. The measurements of the output power were made by calibrating the output voltage of the photodetector with a calibrated power meter, this allowed simultaneous measurement of the output power and laser noise. Each laser showed the normal rapid increase in output power above the laser threshold current. Above threshold the output of the *Y* type of laser varied linearly with laser drive current, whereas as the *1M* and *Q* type devices output characteristics showed some curvature above $\sim 1.2 I_{\text{th}}$. In general, the *Y* type of device was less noisy than the other two types of laser (Fig. 1a and 1b) at $I \simeq 1.4 I_{\text{th}}$ the *Y* device was approximately 10 dB quieter. As is typical with these devices, there is a peak in the noise characteristic which occurs at $\sim I_{\text{th}}$,² although the data is shown only for one frequency (1 kHz) this peak is seen over a wide range of frequencies from 1 Hz to above 100 kHz. The *Y* type of device shows a larger decrease in the relative noise in going from threshold to $\sim 1.4 I_{\text{th}}$ (~ 27.5 dB) than the other devices (~ 22.5 dB). The *Y* type of device also shows a narrower noise peak. If the noise characteristic of the *1M* and *Q* types of laser are superimposed (Fig. 1c, d, e and f) it can be seen that the shape is very similar (note *Q39/2* was somewhat noisier above $1.2 I_{\text{th}}$) although the curves are displaced. A similar result is noted with the *Y* type lasers, although as stated, the *Y* types' peak is much narrower than that of the other lasers. The noise level of all six devices is very good with the exception of *M531*, and is comparable with the quietest lasers observed previously at NRL (e.g., the Mitsubishi TJS ML4307 laser), whereas the *Y* devices are typically 5 dB below this level.

The frequency dependence of the relative noise is shown in Fig. 2 at $1.4 I_{\text{th}}$ and in Fig. 3 at $1.2 I_{\text{th}}$. With the exception of the *Y199/2* laser, at $1.2 I_{\text{th}}$ all the lasers show the typical $\sim \frac{1}{f}$ frequency

dependence of the noise. The Y199/2 device has an average $\sim \frac{1}{f}$ behavior, but the data points have a distinct S shape about the $\frac{1}{f}$ line. Thus, although the intrinsic noise level of these lasers is very low, they exhibit the usual frequency dependence of the noise which has been observed in all the lasers tested at NRL.^{2,13}

MEASUREMENT OF FREQUENCY NOISE

The frequency noise (also referred to as wavelength instability and phase noise when encountered in interferometer systems) exhibited by the Y197/2 laser was measured using a Fabry-Perot interferometer in a non-scanning mode of operation.⁹ The Fabry-Perot mirror separation was adjusted such that the interferometers transmission was held at approximately 70% of the resonance peak maximum. In this condition, frequency fluctuations of the laser source are observed as relatively large fluctuations in the Fabry-Perot transmission intensity. These intensity fluctuations are analyzed by monitoring the Fabry-Perot photodetectors output with a low frequency spectrum analyzer (Tektronix 7LS). The free spectral range of the Fabry-Perot was 5.5 GHz and the finesse ~ 40 , the observed intensity fluctuations due to the frequency instability were a factor of ~ 100 greater than the lasers intrinsic intensity noise. A typical output of the Fabry-Perot interferometer is shown in Fig. 4, as can be seen, the observed noise is ~ 15 dB above the noise floor of the spectrum analyzer. At 2.5 kHz the normalized noise output of the interferometer corresponds to an rms value of ~ 5000 Hz (1 Hz B/W) which is typically a factor of 2 to 3 lower than is typically observed for GaAlAs lasers.⁴ The variation of the frequency noise is shown as a function of the laser drive current in Fig. 5. Above $1.07 I_{th}$ the noise is independent of the drive current. This effect has been seen with other CSP lasers as well as buried heterostructure and transverse junction strip lasers.¹³ As with other GaAlAs lasers, the frequency noise has a $\sim \frac{1}{f}$ frequency dependence.⁴

Optical feedback can effect the spectral characteristics of the semiconductor laser emission. Feedback induced effects investigated at NRL include: emission line narrowing,^{8,9,10} reduction in low frequency wavelength jitter,^{9,10} line broadening,^{7,11} and the appearance of 3 GHz modes in the emission spectra.^{7,11} The first two of these appear at low feedback (r) levels (typically $r < 10^{-4}$), while the other two become evident at high feedback levels ($r > 10^{-3}$, for an external cavity length of 60 cm). All of the above mentioned feedback effects were observed in the Hitachi lasers tested.

Line broadening was of particular interest since when the emission line is sufficiently broadened, the laser coherence length can be made much smaller than the external cavity length. Under this condition, the intensity noise induced by coherent feedback is substantially reduced. Feedback induced line broadening in laser 197/2 is illustrated in Fig. 6a-e. The laser was operating at $I = 1.25 I_{th}$, and the external cavity length was 30 cm. The photographs show Fabry-Perot interferometer (FPI) scans of the laser emission spectrum. The free spectral range (FSR) is 50 GHz (1.2 Å in wavelength) and two FPI orders appear. For the free-running laser, $r = 0$ (Fig. 6a) the linewidth was less than the resolution of the FPI which was 1 GHz at the FSR used. The linewidth was measured to be 15 MHz using a delayed self-heterodyne system.¹⁰ Figure 6b,c show gradual broadening of the emission line and the appearance of side spectral peaks or modes which are approximately 3 GHz away from the main peak. In part c, the three peaks begin to coalesce together. Emission spectra with feedback of 8×10^{-4} and 8×10^{-2} are shown in Fig. 6d,e respectively. The FWHM linewidths are 5.5 GHz in d and 30 GHz in e. The linewidth continued to broaden for further increases in feedback.

Another laser, IM531 exhibited somewhat different line broadening characteristics. The linewidth remained narrower than the free-running laser linewidth for $r < 7 \times 10^{-4}$. At $r = 7 \times 10^{-4}$, the linewidth abruptly changed to 1 GHz and then continued to broaden as the feedback was further increased. Although 3 GHz modes were observed with laser IM531, their intensity was more than one order of magnitude smaller (as a portion of the total output intensity) than in laser 197/2.

INTENSITY NOISE AND OPTICAL FEEDBACK

In this experiment, a small fraction of the laser emission was reflected back into the laser cavity by a mirror placed a few tenths of a mm from the laser facet. The phase of the light fed back into the laser was controlled by mounting the mirror on a piezoelectric cylinder and applying a suitable voltage. As with other GaAlAs lasers investigated at NRL,¹⁴ most phases of feedback have no effect on the intensity noise. However, at certain values of phase the laser begins to spontaneously mode hop between longitudinal modes of the laser cavity. This effect can result in a 40 dB increase in the intensity noise; this effect is shown in Fig. 7a. A sinusoidal voltage was then applied to the piezoelectric cylinder at 1 kHz, such that the mirror scanned over $\sim\pi/4$ radians. Shown in Fig. 7b is the intensity noise produced by the mode hopping and by the shift in threshold due to the perturbation of the reflector, this appears at 1, 2, 3, 4 kHz. Shown in Fig. 7c is the intensity noise produced when the dc phase shift is adjusted so that the laser remains in one longitudinal mode. As can be seen, the broadband noise reduces to the free-running laser noise. It should be noted that the 2nd, 3rd, and 4th harmonics of the fundamental are still present indicating considerable distortion.

CONCLUSIONS

When free-running, the six lasers investigated were found to be typically 10-20 dB quieter than conventional GaAlAs lasers. As well as the reduced intensity noise, the frequency noise of the Y197/2 laser was a factor of 2 to 3 lower than other types of semiconductor laser. These reductions in the intrinsic noise of the laser allows a relaxation of (a) path length matching (to reduce phase noise) and, (b) optical intensity balancing (to reduce intensity noise) requirements necessary for fiber optic interferometer sensors. The low values of intensity noise also make these devices attractive for use in the diode laser sensor which typically is intensity noise limited.¹⁵

The behavior of these lasers in the presence of optical feedback into the laser cavity is similar to other GaAlAs lasers investigated. Consequently, the precautions taken to eliminate reflections into the laser cavity are still required.

ACKNOWLEDGMENTS

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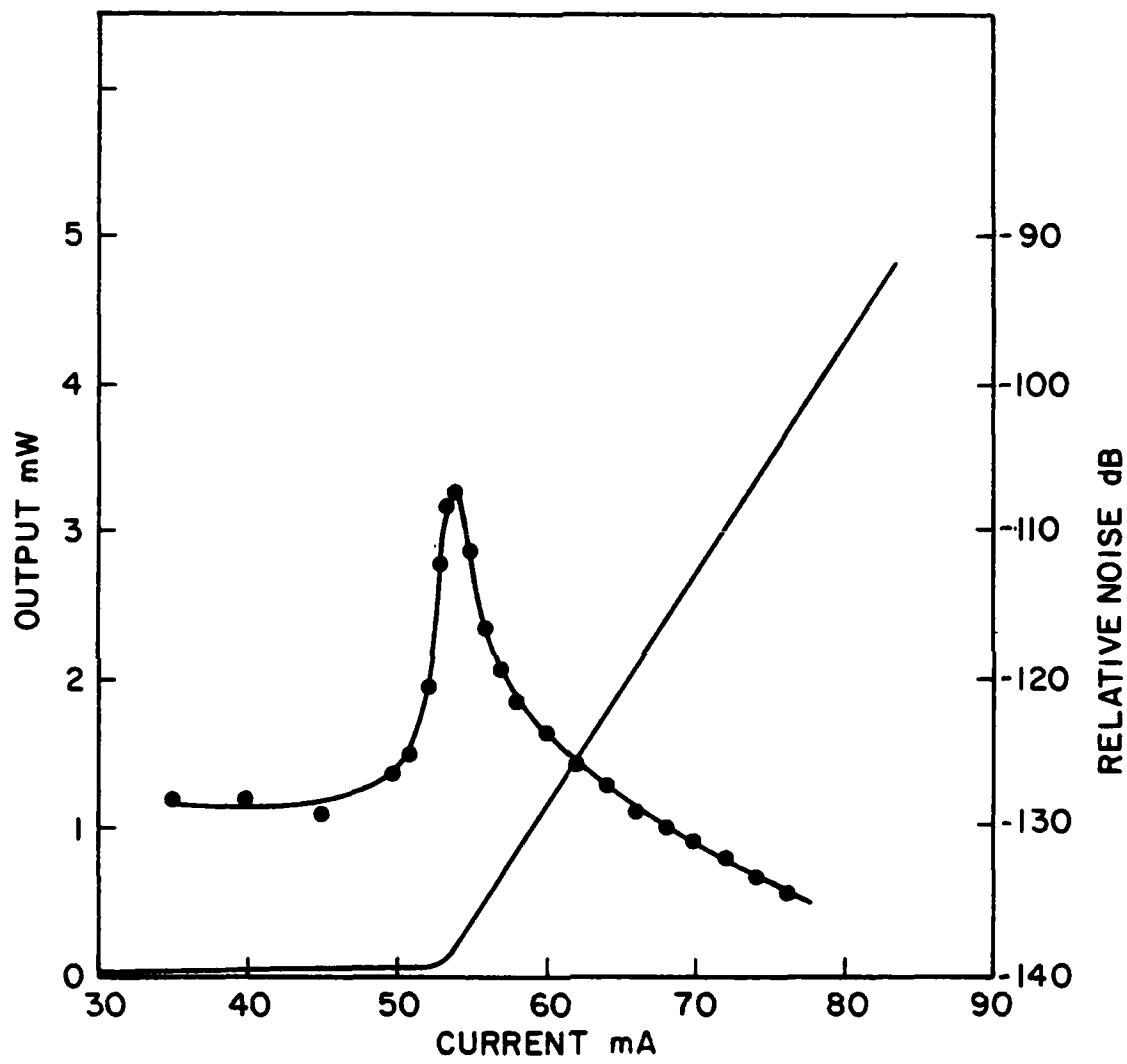


Figure 1a — Power output and relative intensity noise (at 1 kHz with a 1 Hz B/W) as a function of laser driving current for laser Y197/2

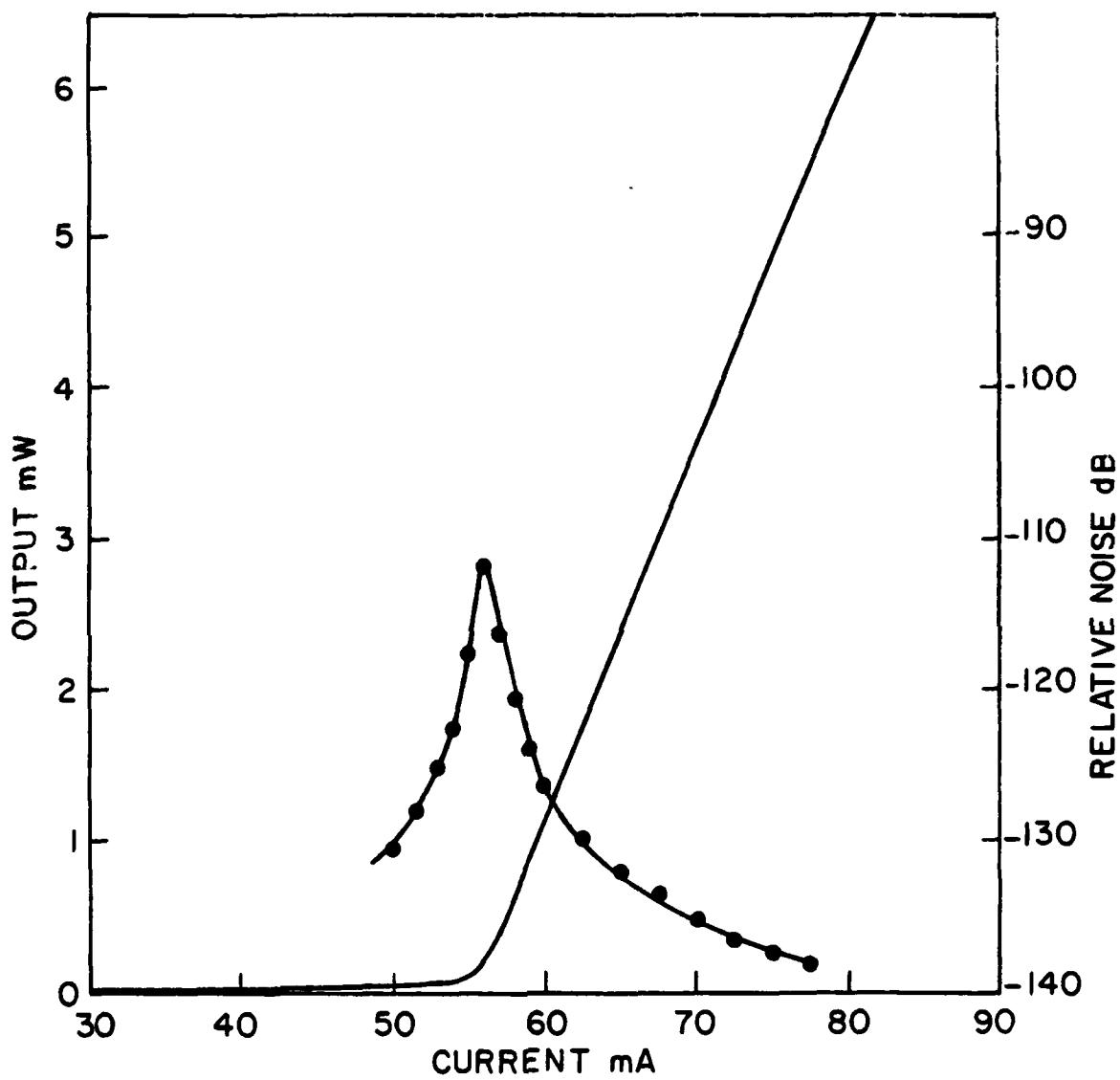


Figure 1b — Power output and relative intensity noise as a function of laser driving current for laser Y199/2

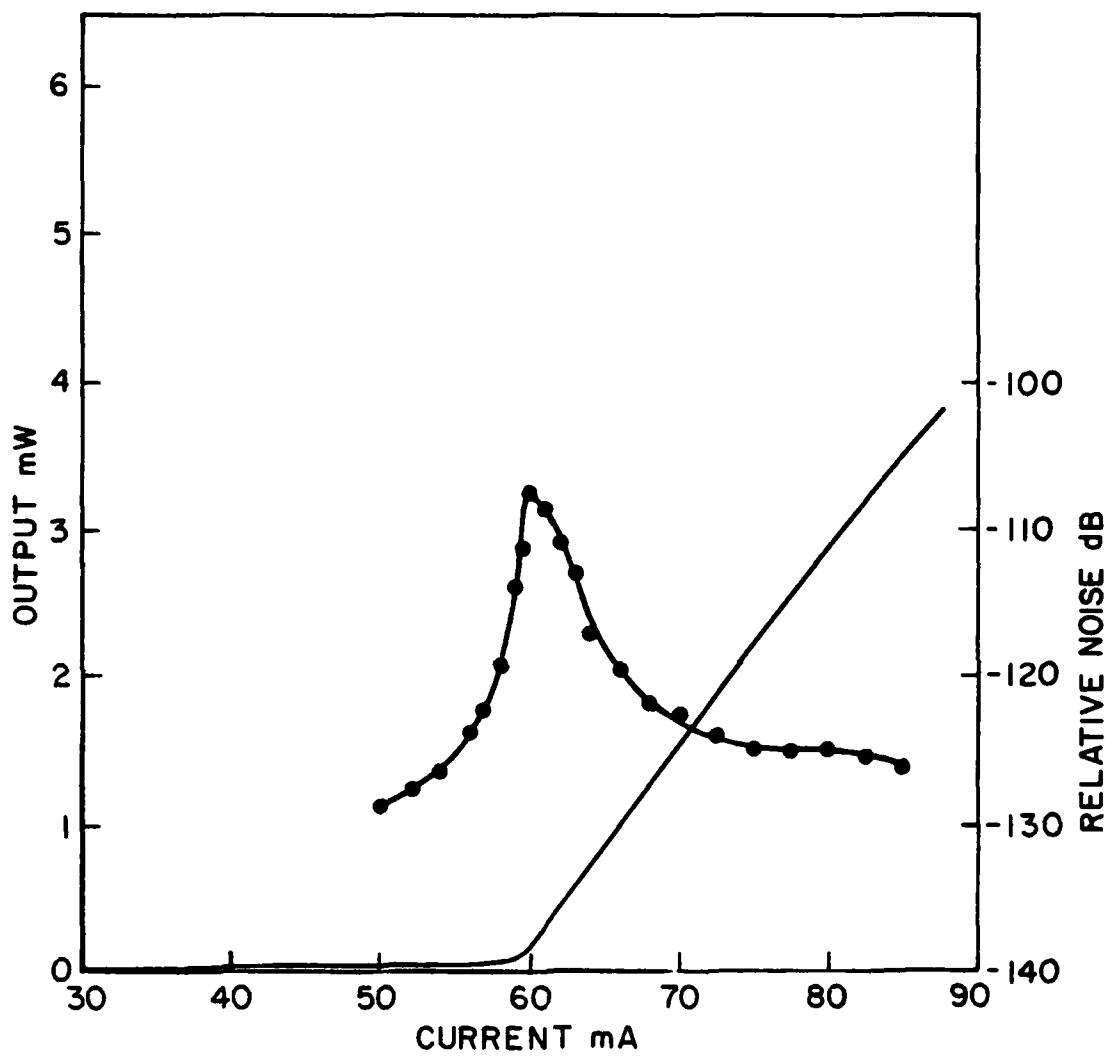


Figure 1c — Power output and relative intensity noise as a function of laser driving current for laser Q39/2

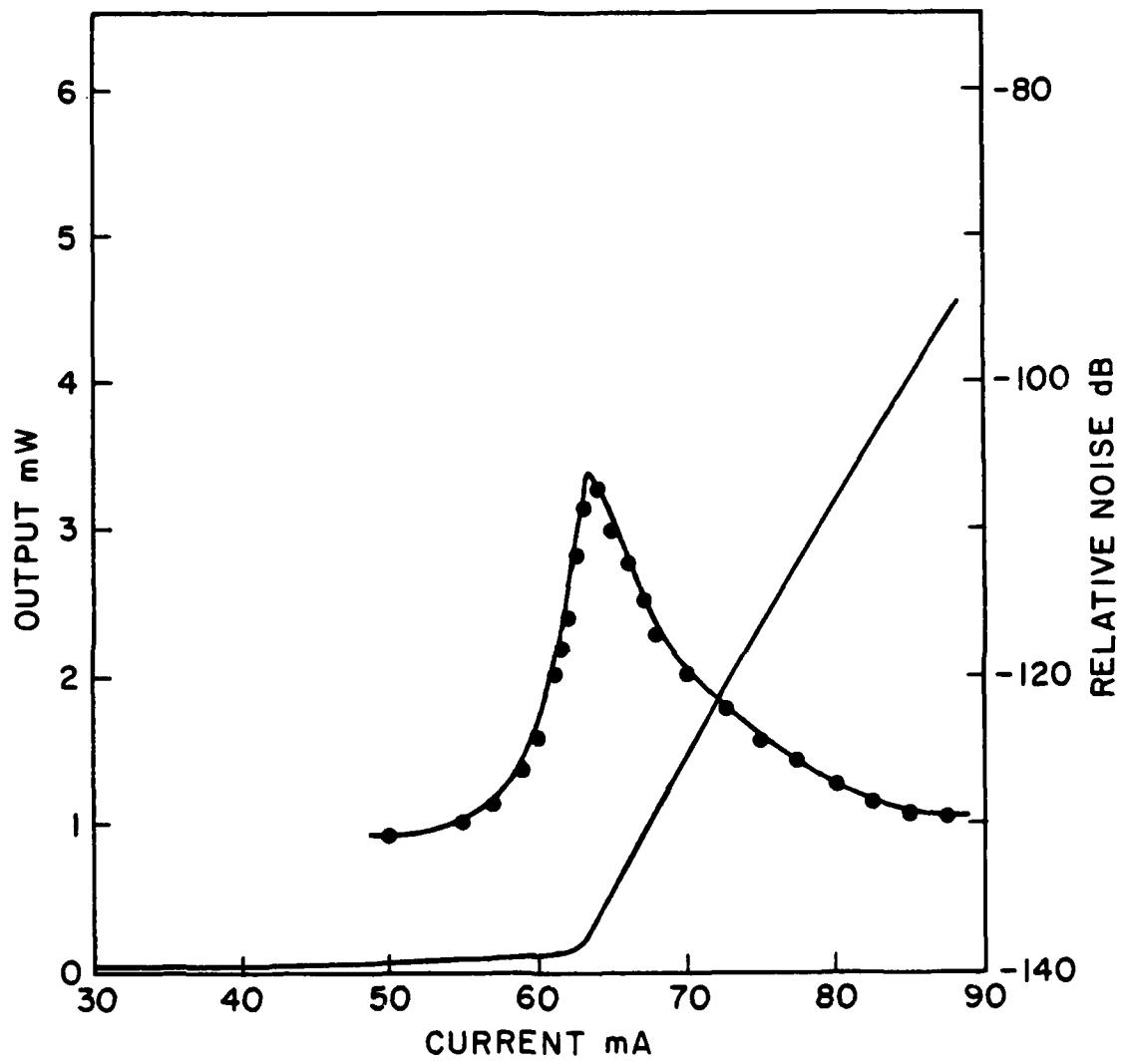


Figure 1d — Power output and relative intensity noise as a function of laser driving current for laser Q39/3

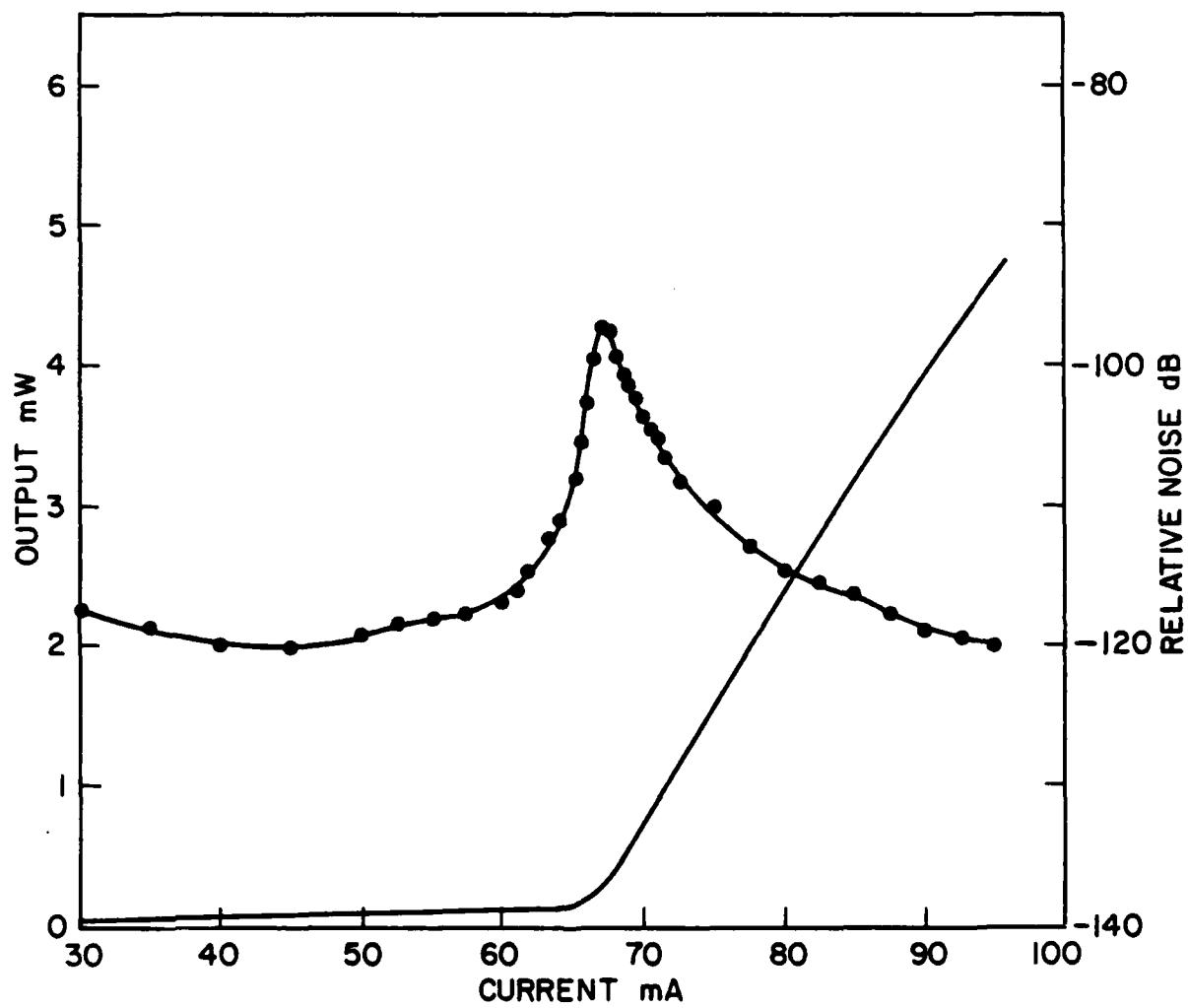


Figure 1e — Power output and relative intensity noise as a function of laser driving current for laser 1M531

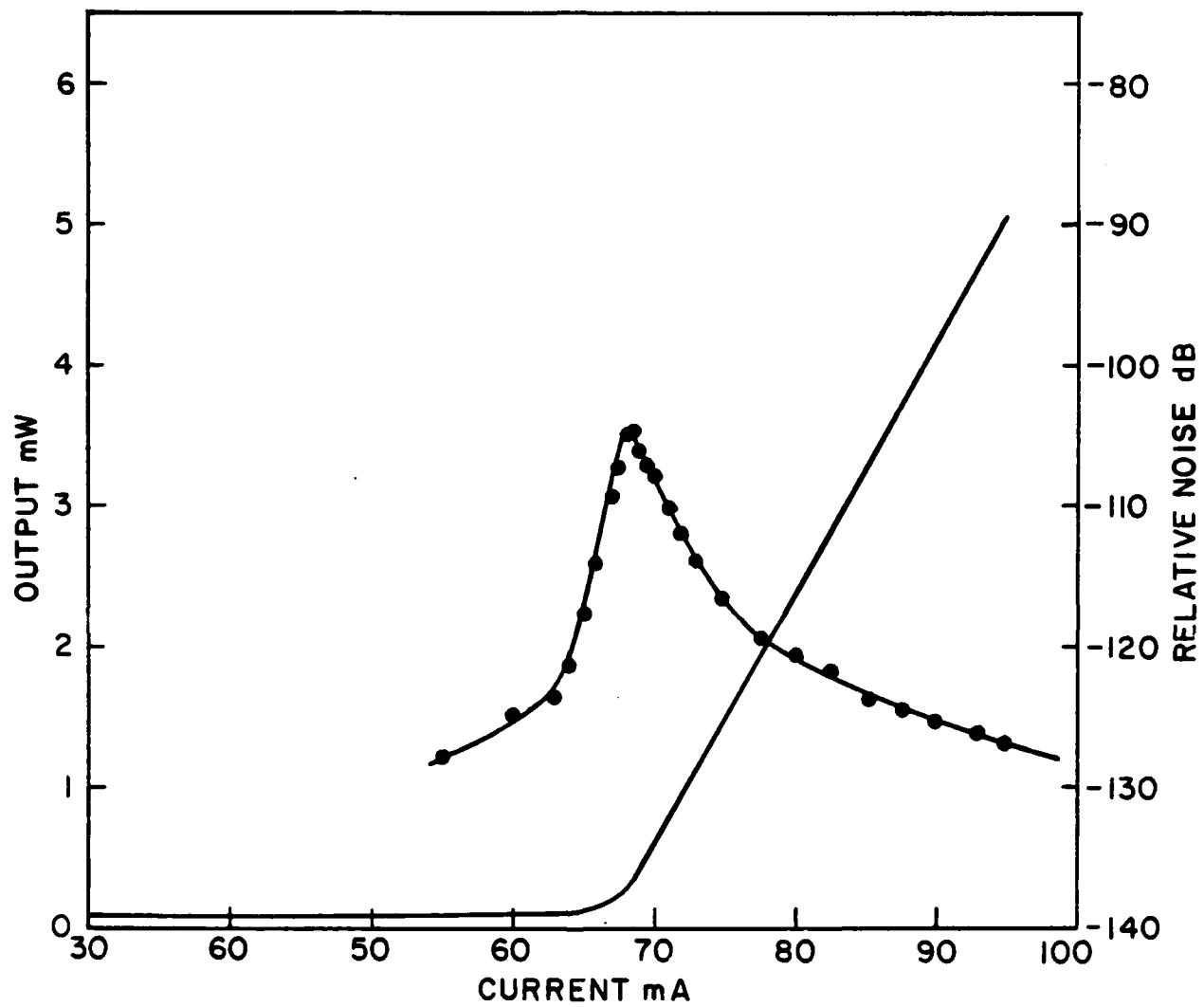


Figure 1f — Power output and relative intensity noise as a function of laser driving current for laser 1M532

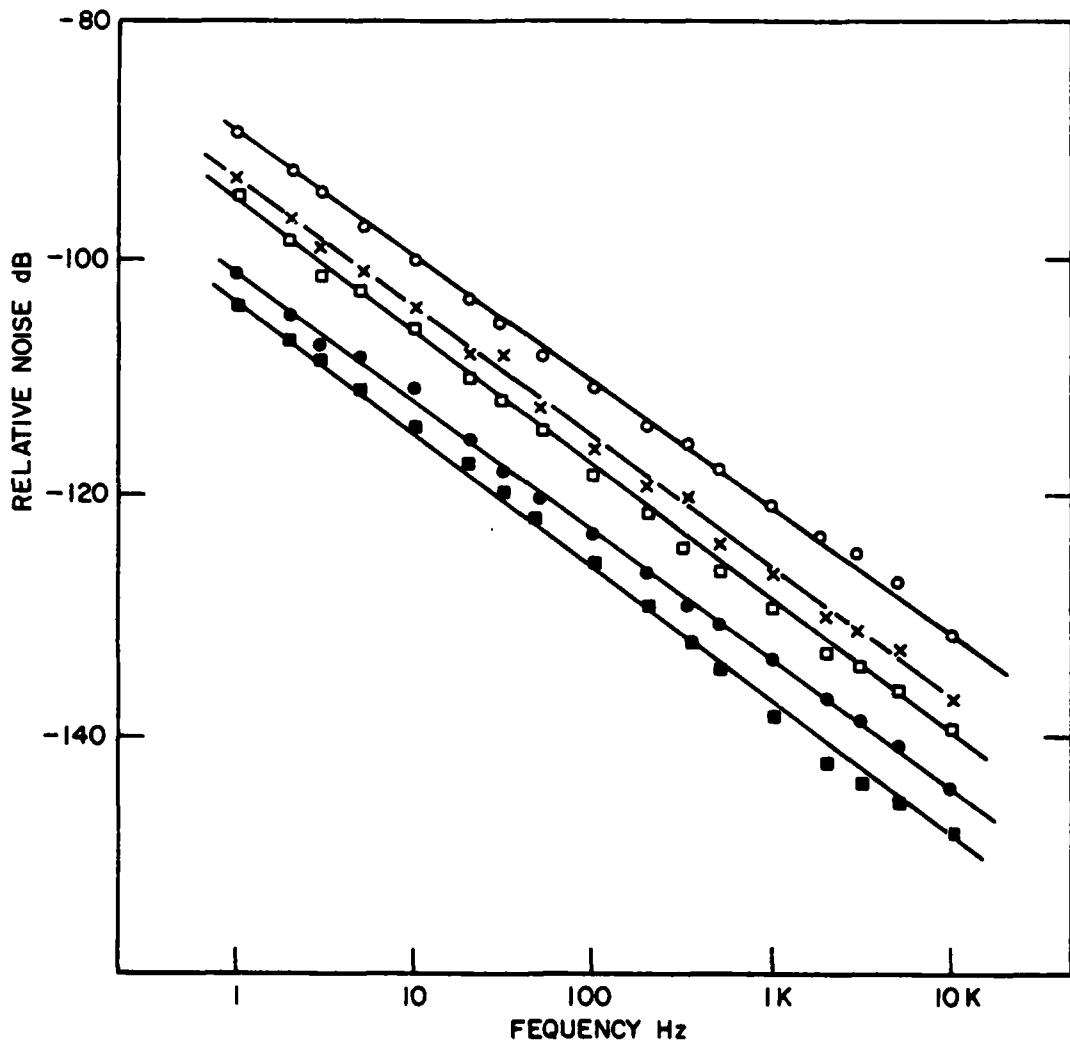


Figure 2 — Variation of the relative noise with frequency at $1.4 I_{th}$ for the six lasers tested. o, 1M531;
x, Q39/2; □, Q39/3; ●, Y197/2; ■, Y199/2. Laser 1M532 omitted for clarity.

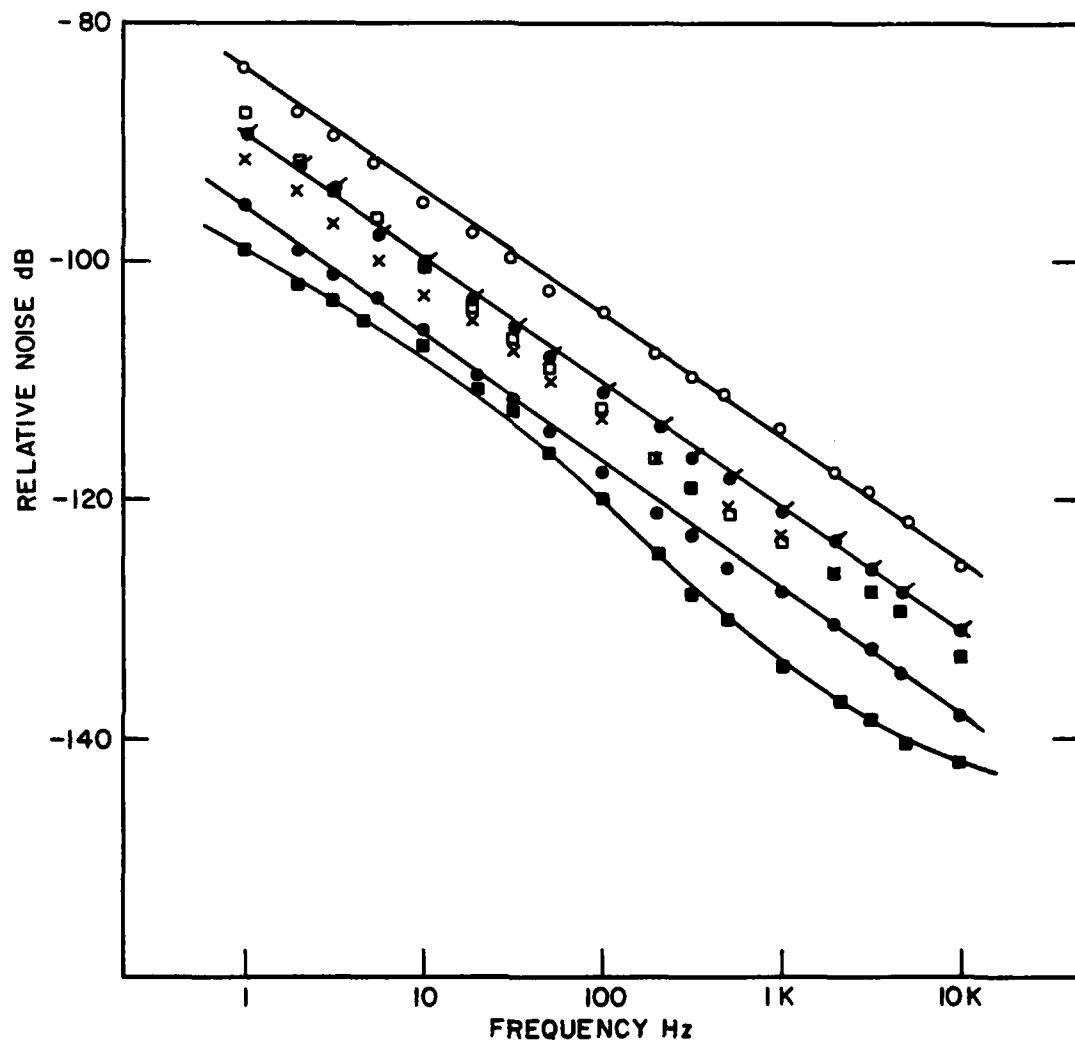


Figure 3 — Variation of the relative intensity noise with frequency at $1.2 I_{th}$ for the six lasers tested.
 o, 1M531; ●, 1M532; ×, Q39/2; □, Q39/3; ●, Y197/2; ■, Y199/2

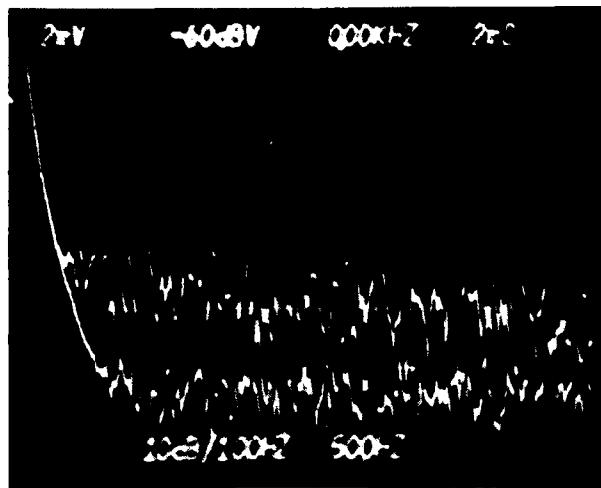


Figure 4 — Frequency noise. Upper trace, output noise of Fabry-Perot interferometer set at maximum slope of the transmission function, source: Y197/2. Lower trace: noise floor of spectrum analyzer. Each vertical division is 10 dBV, each horizontal in 500 Hz ($B/W = 100$ Hz).

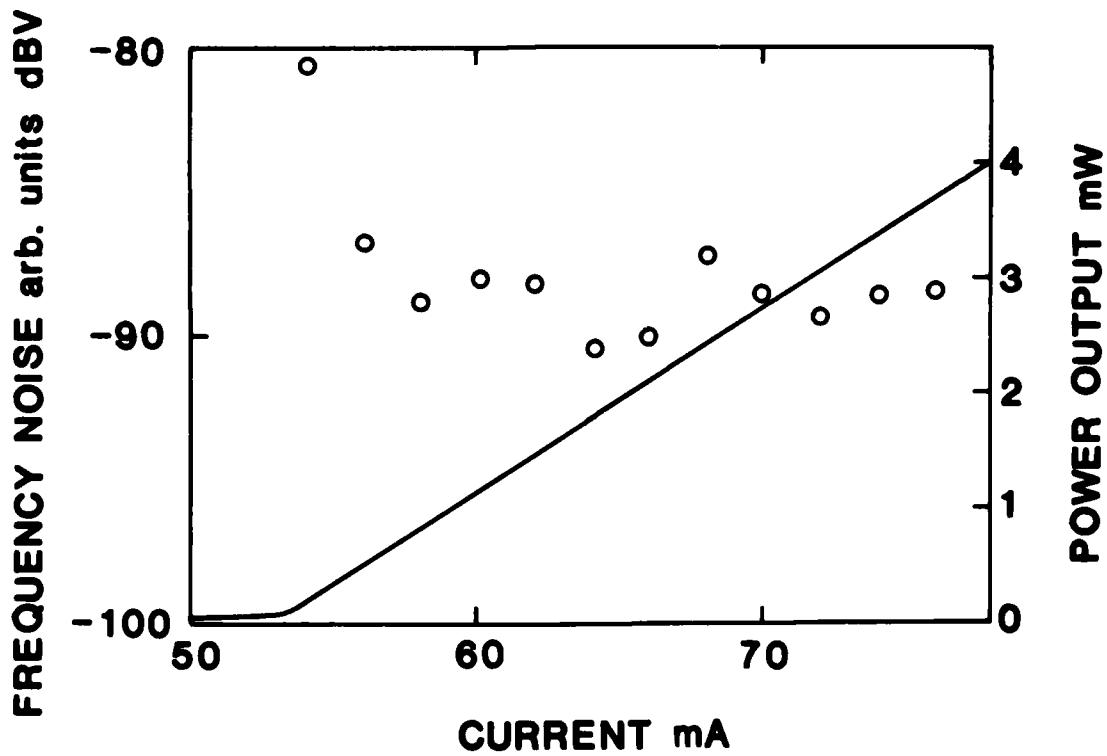


Figure 5 — Variation of the output power and frequency noise with laser drive current for the Y197/2 laser. The mean value corresponds to an rms frequency instability of ~ 5000 Hz (at 2.5 kHz with a 1 Hz B/W).

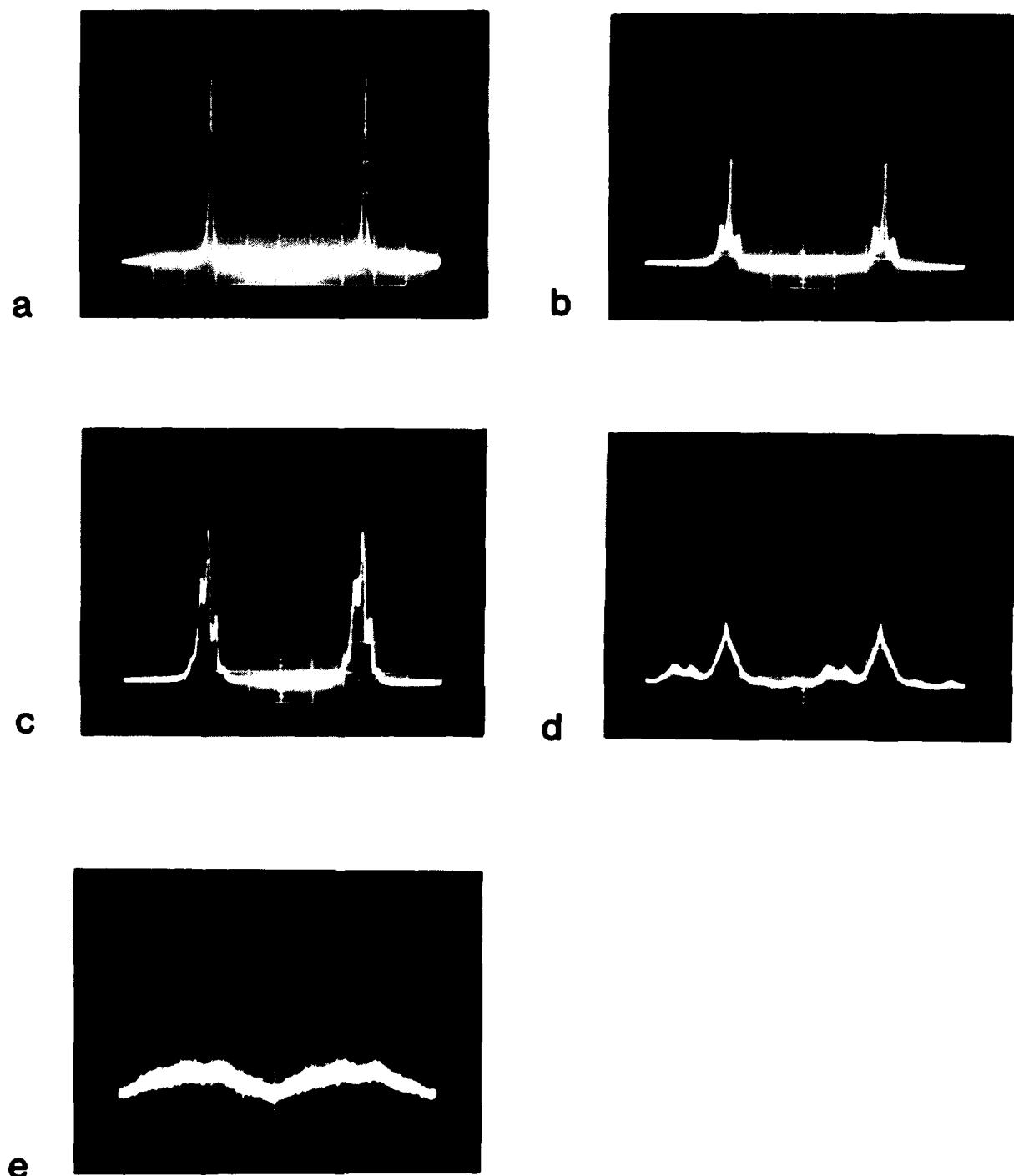


Figure 6 — Fabry-Perot interferometer scans of emission spectra of laser Y197/2 ($I = 1.25 I_{th}$) with feedback of (a) $r = 0$, (b) $r = 2 \times 10^{-5}$, (c) $r = 10^{-4}$, (d) $r = 8 \times 10^{-4}$, (e) $r = 8 \times 10^{-2}$. The Fabry-Perot interferometer's free spectral range is 50 GHz and two spectral orders appear in each case.

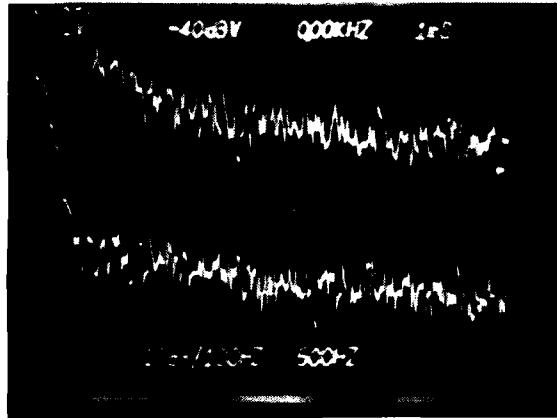


Figure 7a — Feedback induced intensity noise. Upper trace shows the intensity noise when the laser is mode hopping, lower trace shows intensity when phase of optical feedback is adjusted away from the feedback induced unstable position.



Figure 7b — Upper trace: sinusoidal $\pm \lambda/8$ signal applied to mirror at 1 kHz, dc phase adjusted to induce mode hopping. Lower trace: free-running laser.

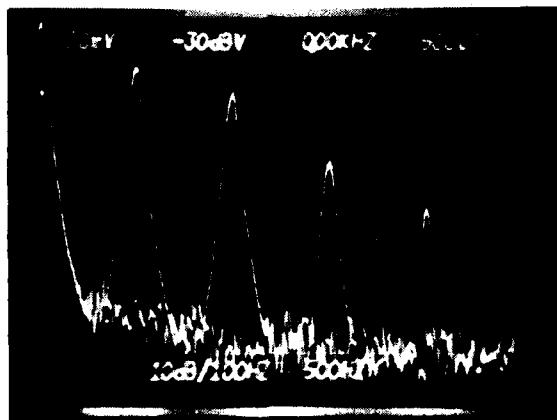


Figure 7c — Upper trace: sinusoidal $\pm \lambda/8$ signal applied to mirror at 1 kHz, dc phase adjusted to stable (nonhopping) position. Lower trace: free-running laser.